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OPTIMAL UAV TASK ASSIGNMENT AND SCHEDULING (PREPRINT)

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14. ABSTRACT
This paper addresses the issue of task assignment and scheduling for teams of cooperative Unmanned Aerial Vehicles (UAVs) operating in a semi-autonomous manner with a single operator controlling the multiple-vehicle team. Mixed-Integer Linear Programming (MILP) is a highly effective technique for expressing this type of complex optimization problem because it allows for binary decision variables, continuous timing variables, and an extensive, flexible constraint set. A general MILP formulation is proposed, allowing a wide variety of vehicle capabilities and mission requirements to be incorporated. Possible task coupling constraints include precedence constraints, time windows, simultaneous tasks, joint tasks, and more. A variety of scenarios, with heterogeneous vehicles, and a wide range of mission constraints can be addressed.

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Optimal UAV Task Assignment and Scheduling

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Overview

- **Introduction**
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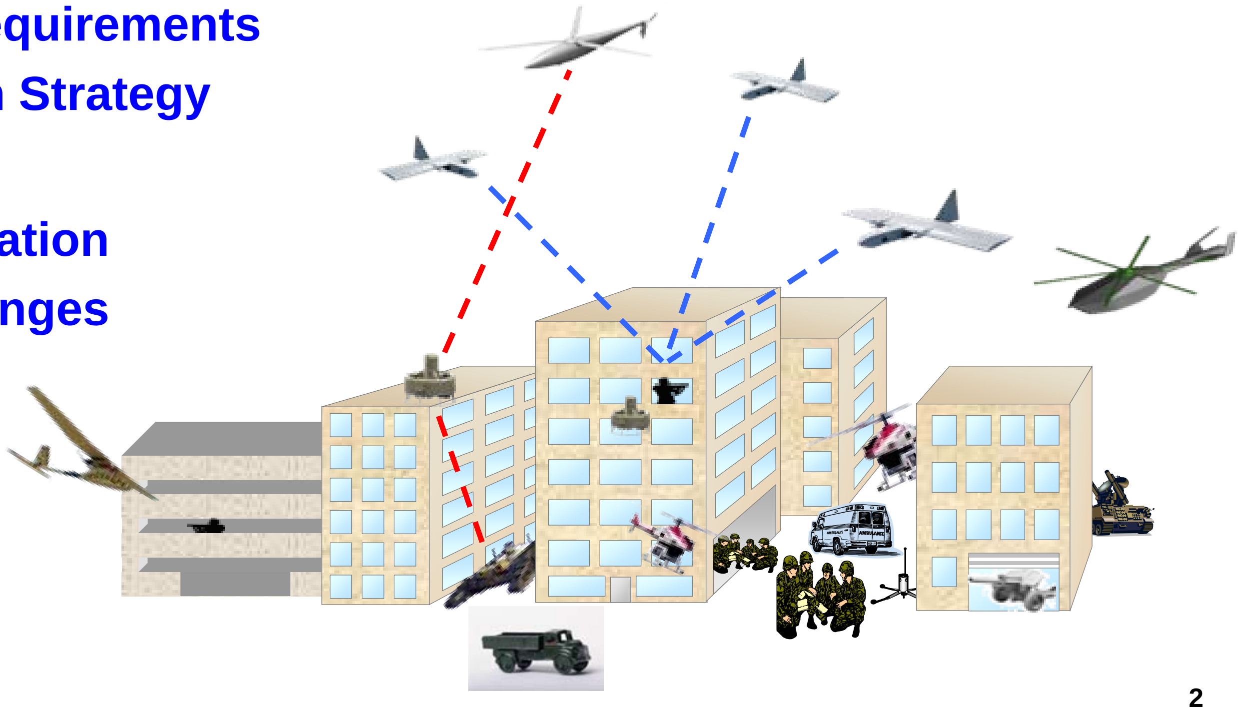
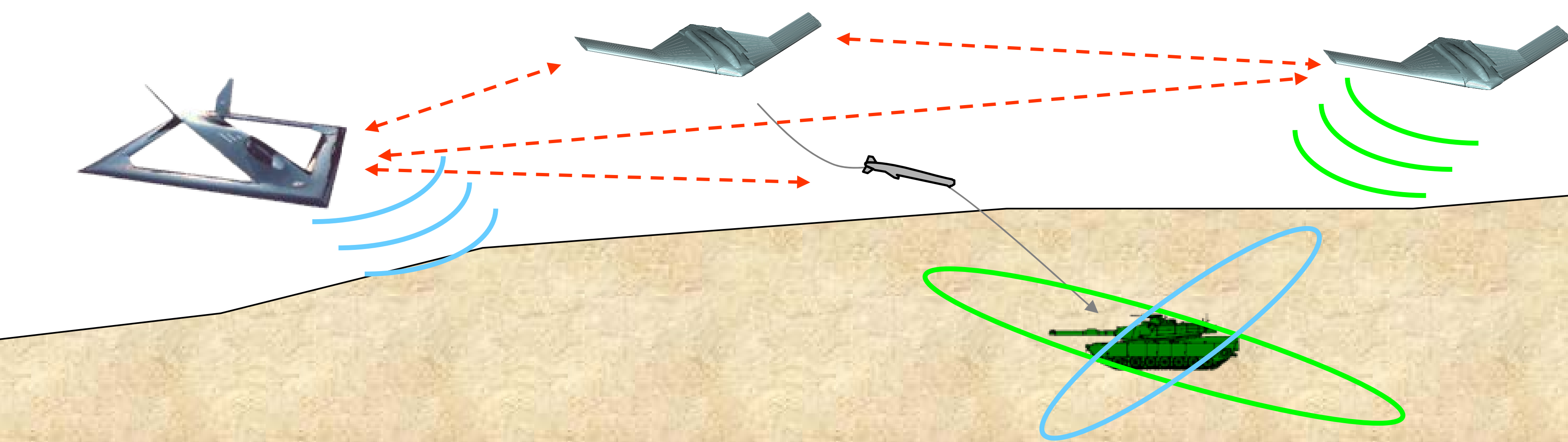
  - **Scenario Description**
- **Task Assignment and Scheduling**
  - **MILP Formulation**
  - **Task Planning Examples**
  - **Computational Requirements**
  - **Alternate Solution Strategy**
- **Conclusions**
  - **Flight Test Application**
  - **Long Term Challenges**



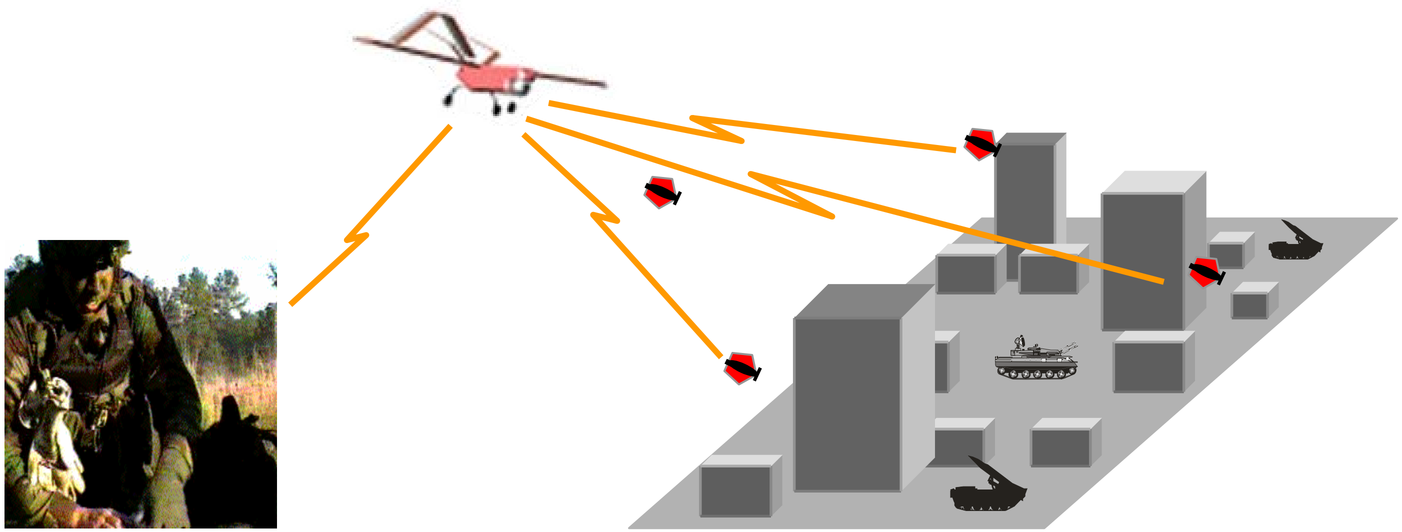
Introduction

- **Coupled Task Assignment and Scheduling Problems**
  - Examples:
    - Laser designation and attack
    - Cooperative Tracking
    - Serial tasks, e.g. Classify => Attack => Verify
  - Highly coupled mission planning problems are computationally difficult
    - Small problem sizes allow optimal solution in “real time”
    - Suboptimal but effective solutions computable faster
  - Combat ISR UAV Example



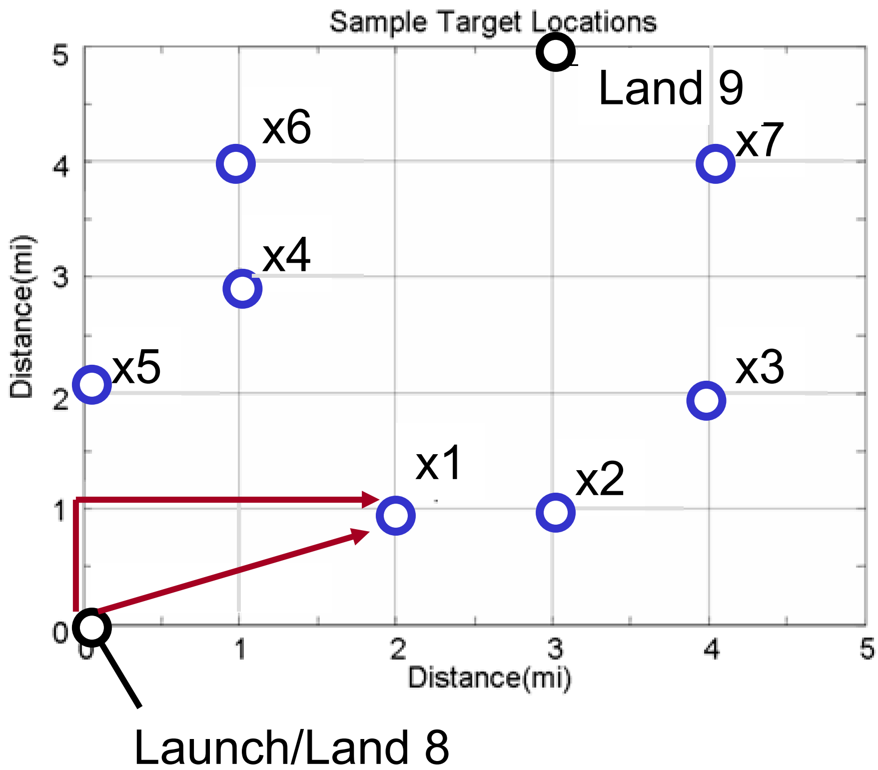
Introduction

- **Scenario**
  - Multiple unmanned aerial vehicles (UAVs) in an urban environment
  - Target locations known
  - Each target requires the assignment of 1-2 UAVs
  - Urban terrain (rectilinear distance appropriate)
  - Supervised by a single operator
  - Operator has the ability to impose additional timing constraints



Urban Combat ISR Scenario Setup

- Potential Target locations 1-7
- All MAVs launch from node 8
- MAVS can land at node 8 or 9
- Path distances calculated, in the examples, using a “Manhattan Grid” path down the streets, plus loiter
  - ➢ Could be Euclidean, flyable paths, etc…
- Each Target requires two tasks: “attack” and “verify”
  - ➢ *t = 0.1* delay required between tasks



- Three UAV types:
  - ➢ Type 1: can attack (Task 1)
  - ➢ Type 2: can verify (Task 2)
  - ➢ Type 3: can attack or verify
  - ➢ # Attacks per vehicle limited
  - ➢ Different task execution times for each vehicle type, target, task

x_{ij}^{kl}

MILP Formulation - Variables

- Binary Decision Variables:
  - x_{ij}^{kl} = 1 if UAV *k* is assigned to travel from node *i* to node *j* and perform task *l* on target *j*, = 0 otherwise
- Continuous timing variables:
  - t_i^l is a continuous variable which indicates the arrival time of a UAV at target *i* to perform task
  - t_{lk} is also a continuous variable, but indicates when each UAV will land at each landing site

MILP Formulation - Cost Functions

- Three cost functions examined:
- Minimum total path length:

$$\sum_{l=1}^{2} \sum_{i=0}^{N} \sum_{j=0}^{N} \sum_{k=1}^{K} c_{ij} x_{ij}^{kl}$$

- Minimum makespan (shortest time to complete all tasks):

$$\min \max (t_{jk})$$

- Minimum total task execution time for all vehicles:

$$\sum_{i=N+L+1}^{N+L+C} \sum_{k=1}^{K} t_{jk}$$

- Cost Functions 2 and 3 include task execution and loiter times, Cost Function 1 (total path length) does not

Mission Constraints (Selected Examples)

Each target requires both tasks be performed:

$$\sum_{k=1}^{K} \sum_{j=1, j\neq i}^{N} x_{ij}^{kl} = 1 \quad \forall\, i \in [1, N], l \in [1,2]$$

Every vehicle that enters a target must also exit (flow balance):

$$\sum_{l=1}^{2} \sum_{i=1, i\neq h}^{N} x_{ih}^{kl} - \sum_{l=1}^{2} \sum_{j=1, j\neq h}^{N} x_{hj}^{kl} = 0 \quad \forall h \in [1, N], k \in [1, K]$$

Each target must have two arrival times (one for each task)

$$t_i^l + t_{ij}^{kl} + s_i^l - M(1 - x_{ij}^{kl}) \leq t_j^l \quad \forall i \in [1, N+L], j \in [1, N], k \in [1, K], l \in [1,2], i \neq j$$

Operator-specified constraints

- Human Operator of UAV team must be able to control UAV actions at desired levels – “as autonomous as needed, as interactive as desired”
  - In response to urgent mission needs, commander instructions
  - Planning algorithms should incorporate operator input, optimize around those requirements
  - Implemented in MILP as additional constraints, e.g.

Targets *a*, *b, c* residing in the same cluster must be simultaneously attacked:

$$t_a^1 = t_b^1 = \mathrm{t}_\mathrm{c}^1 \quad \text{such that} \quad a, b, c \in [1, N]$$

Target *a* must be verified destroyed before target *b* can be attacked:

$$t_a^2 \le t_b^1 \quad \text{such that} \quad a, b \in [1, N]$$

- More complex constraints, e.g. time windows, also allowable

Task Planning Example

Four Vehicles:

- V1, V2 – Attack only
- V3 – Image only
- V4 – Attack (3 times), Image
- All start at origin, end at origin or alternate end point

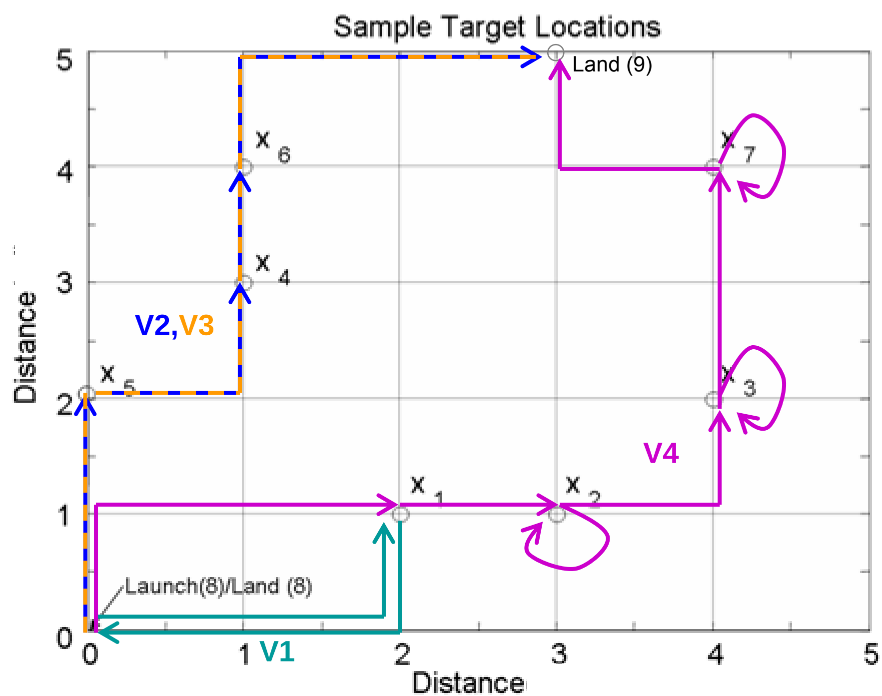
Cost function: min total path length

Vehicles 2, 3 “team up” on Targets 5,4,6

Vehicle 4 teams up with Vehicle 1 on Target 1, then prosecutes Targets 2,3,7

- V4 limited to being able to attack 3 times only.

Vehicle Task Assignment



Example with Additional Operator-Specified Constraints

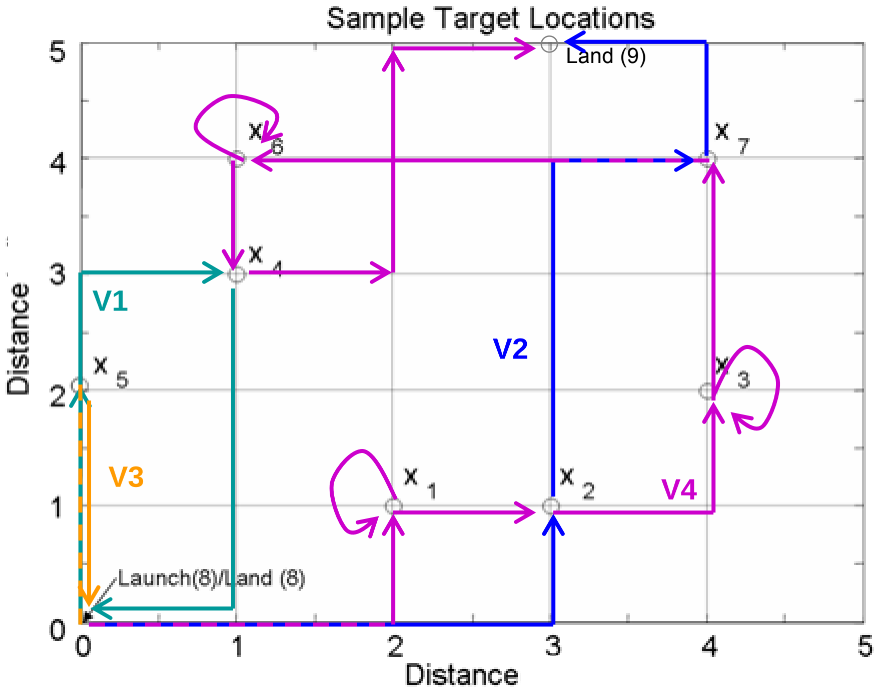
Additional Constraints:

- Targets 1, 2 attacked simultaneously
- Targets 4, 6 attacked simultaneously
- Target 2 verified destroyed before Target 3 attacked

Assignment changed substantially:

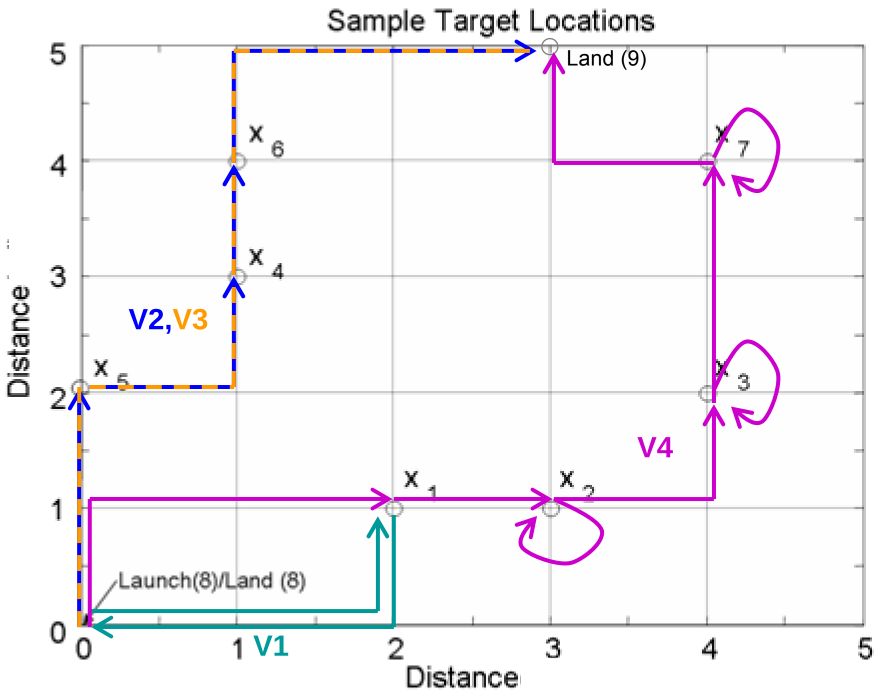
- V1 attacks T5 (t=0.08), T4 (t=1.5)
- V2 attacks T2 (t=0.16), and T7 (t=1.18)
- V3 images T5 (t=0.18)
- V4 has a complex mission plan:
  - Attack T1 (t=0.16)
  - Image T1 (t=0.26)
  - Image T2 (t=0.40)
  - Attack T3 (t=0.58), Image (t=0.68)
  - Image T7 (t=0.1.28)
  - Attack and Image T6 (t=1.5, 1.6)
  - Image T4 (t = 1.74)

Task Assignment with Operator-Specified Constraints

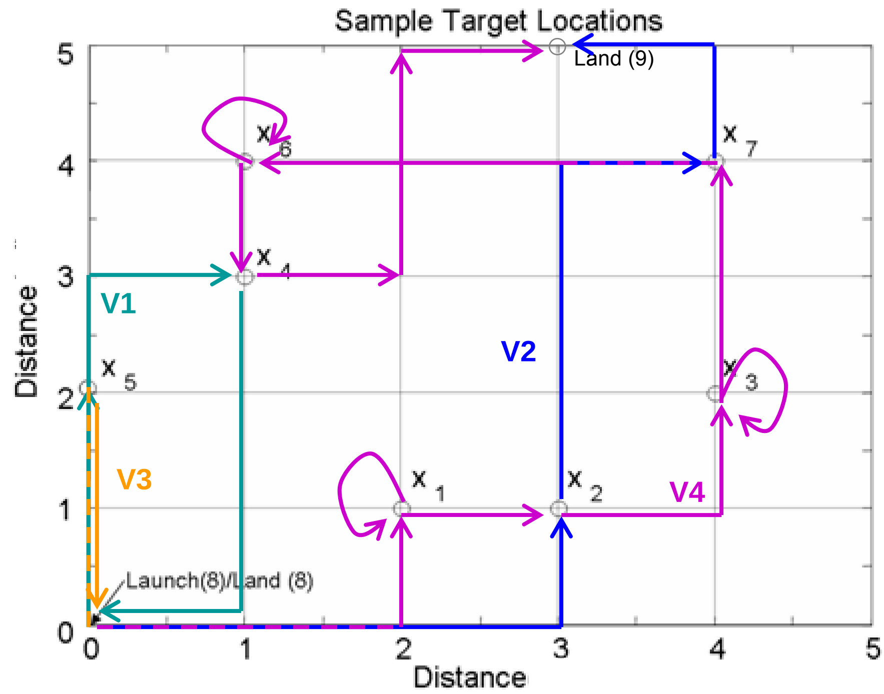


Side by Side Comparison

Vehicle Task Assignment



Task Assignment with Operator-Specified Constraints



- Substantial changes in task assignment schedule based on operator-specified constraints
- Illustrates flexibility of the planning methodology

Computation Times – "Total Distance" Objective Function

N	K1	K2	K3	L	C	Decision Variables	Constraints	Computation Time(s) Distance	Min	Max
2	1	1	1	1	1	27	59	0.051	0.043	0.499
3	2	2	0	2	1	70	89	0.066	0.061	0.080
3	2	2	1	1	1	74	137	0.062	0.053	0.097
4	1	1	0	2	1	58	72	0.058	0.047	0.092
4	0	0	2	1	2	68	210	0.140	0.057	0.778
4	1	1	2	1	1	100	254	0.446	0.091	3.804
5	1	1	1	2	2	141	273	1.213	0.096	11.702
5	1	0	2	1	1	113	328	1.051	0.141	8.840
6	1	1	1	1	2	168	325	8.309	0.201	115.00

Table 1: Computation Times for the Total Distance Objective

- **K1 = # Task 1 Vehicles**
- **K2 = # Task 2 Vehicles**
- **K3 = # Task 1 or 2 Vehicles**

- **N = # Targets**
- **L = # Launch sites**
- **C = # Landing sites**

Computation Times – Alternate Objective Functions

N	K1	K2	K3	L	C	Decision Variables	Constraints	Computation Time(s) Makespan	Min	Max
2	1	1	1	1	1	27	59	0.062	0.054	0.074
3	2	2	0	2	1	70	89	0.217	0.106	0.336
3	2	2	1	1	1	74	137	0.235	0.109	0.345
4	1	1	0	2	1	58	72	0.573	0.191	0.895
4	0	0	2	1	2	68	210	73.606	52.215	104.207
4	1	1	2	1	1	100	254	108.894	57.448	162.366
5	1	1	1	2	2	141	273	15,352*	12,099	18,606

Makespan Objective

N	K1	K2	K3	L	C	Decision Variables	Constraints	Computation Time(s) Total Time	Min	Max
2	1	1	1	1	1	27	59	0.062	0.054	0.081
3	2	2	0	2	1	70	89	0.303	0.177	0.374
3	2	2	1	1	1	74	137	0.364	0.304	0.413
4	1	1	0	2	1	58	72	0.841	0.340	1.850
4	0	0	2	1	2	68	210	166.10	96.59	273.34
4	1	1	2	1	1	100	254	538.71	275.9	703.7

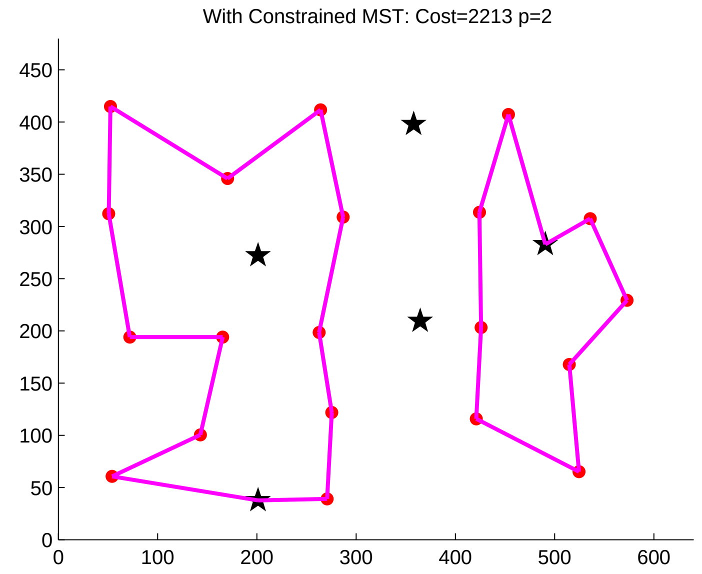
Total Time Objective

Dramatically longer computation times just by varying cost function

Ongoing Work: Primal-Dual Approaches to Assignment of Highly Coupled Tasks

- **Basic Strategy: Extension of dual formulation approaches for TSP to provide:**
  - ➢ **Bounds on optimal cost**
  - ➢ **Near-optimal solutions**
    - **Within 1-2% for TSP**
- **Difficulties:**
  - ➢ **Multiple Vehicles lead to MDMTSP (Multiple Depot Multiple Traveling Salesman Problem)**
    - **No direct transformation to TSP**
    - **Complex connectivity constraints**
  - ➢ **Task Coupling Constraints**
    - **Timing, Precedence, etc...**

- **Goal: Computationally efficient guaranteed near optimal solutions**



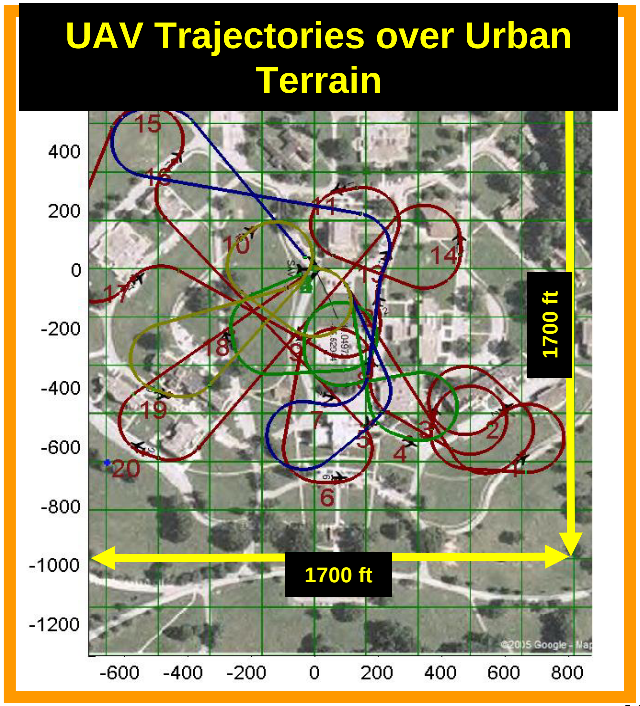
- **Example - Solution to MTSP**
  - ➢ **Branch and bound with Lagrangean relaxation**
  - ➢ **Optimal solution uses 2 of 5 vehicles**
    - **Minimum total path length traveled, not minimum prosecution time**

Urban ISR Application

•*Autonomous control*
•*Multiple heterogeneous UAVs*
•*Supervised by a single operator*

Real time ISR delivery to war fighter

Flight Test
Algorithm Solution



Summary

- Mixed Integer Linear Programming is a good planning strategy
  - Limited to small teams by computational requirements
  - Fits many realistic team sizes
    - Usually multiple people controlling one UAV, not the reverse.
  - “Suboptimal” implementation can somewhat improve computational burden
    - Quality of suboptimal solutions is unclear

- Pursuing dual formulation strategy that may yield good suboptimal solutions with bounded performance

Long Term Challenges in UAV Cooperation

Human Interaction

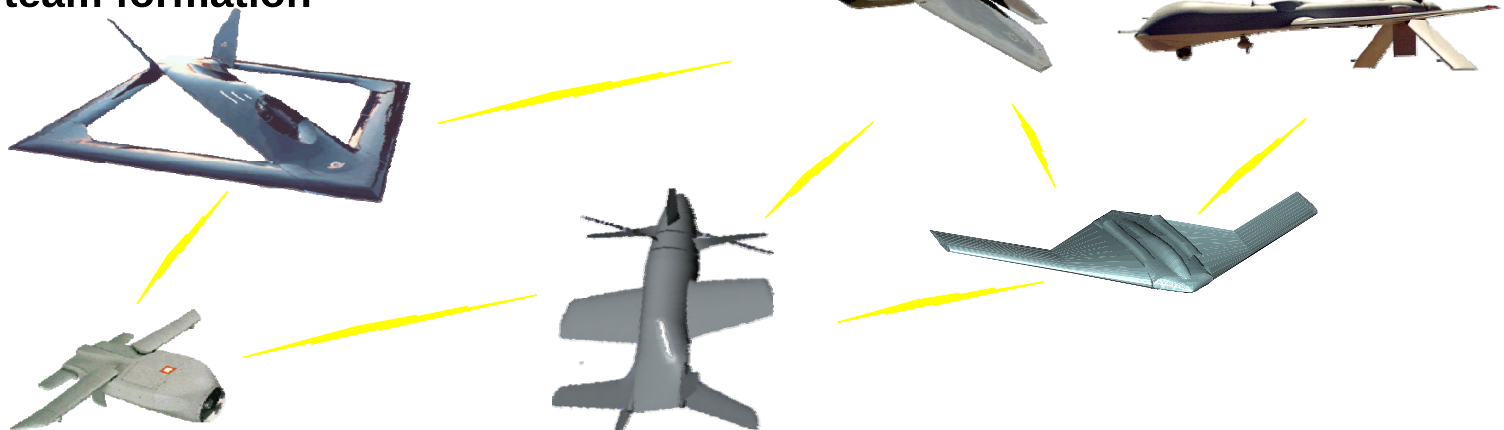
- Multiple operators for one UAV
    - Much work being done to improve the ratio
- Information abstraction & presentation
- Manned Systems

Adversary Interaction & Uncertainty

- Static planning algorithms don’t react well to a dynamic environment
    - Learning new parameters is too slow
    - ESPECIALLY poor for “Out of the box” events

Ad Hoc Collaboration / Dynamic Teaming

- Cooperative Team concepts are generally homogeneous, purpose-built
- Goal: maximize utility of resource-constrained assets in an ad hoc manner
    - System of systems environment
    - Dynamic team formation



Questions?

Flight Test Micro UAVs